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A method to generate constrained terrain following trajectory using circular path

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Abstract
Terrain following(TF) flight could minimize the risks to be revealed by enemy while having proper trajectory. There are some constraints on initial position and terminal position of TF trajectory because TF trajectory should reflect the terrain profile and the aircraft position. In this paper, the method to generate constrained TF trajectory is proposed. The circular path method is conducted to TF path which is generated by using 3-mask morphology. After generating TF path, it is converted into TF trajectory. Generated TF trajectory is confirmed that the aircraft could follow by the tracking simulation.

1. Introduction

In military aviation, avoiding the enemy's radar is one of the important strategies.[1-3] Terrain following(TF) requires a proper trajectory to reduce the risk of being revealed to the enemy while maintaining the clearance height.[3] The proper trajectory stems from the proper terrain profile. The fighter aircraft usually utilize not only its own radar but also the digital terrain database. The terrain profile can be generated by using only radar scan data, using only a digital terrain database, and using both. When using radar scan data, gathered radar scan data can have a limitation of the radar max range. As a result, terrain profile is generated with a certain frequency. Therefore, the trajectory also needs to be generated at a certain frequency. It refers that there are some constraints, including the initial and terminal positions of TF trajectory.
The problems of TF trajectory generation have been studied by applying the concepts of optimal control/optimization.[4, 5] A cubic-B-Spline is utilized to approximate the optimal TF trajectory and determine the coefficient of the spline to minimize altitude error to generate the optimal trajectory.[5] The inverse dynamics approach is applied to deal with generating the optimal TF trajectory and generating TF trajectory using sequential quadratic programming.[6] The objective of the research is to minimize the flight time and the altitude difference with terrain. When generating TF trajectory with the concepts of optimal control/optimization, it might be difficult to apply in real time due to the complexity of the computation, and it often takes a long time to derive results or does not converge values.[7]
In this paper, a constrained TF trajectory generation algorithm is proposed. While generating the TF trajectory, there are several considerations. The generated TF trajectory should satisfy the considerations and constraints. It is assumed that the terrain profile is generated by using radar scan data which is gathered in the DTED Level 2 environment. The terrain profile maintains a similar altitude with the terrain (DTED Level 2) until 4km away from the aircraft position. Generally, TF only considers longitudinal motion along the aircraft's path.[2,3] Therefore, TF trajectory is generated based on the 2-dimensional terrain profile of 4km. As a first step, 3-mask morphology[8] is used to generate the TF path which satisfies the clearance height and clime/dive angle limits. Next, the circular path is used to make TF path smooth, and it satisfies the normal acceleration limits and climb/dive angle limits. In this case, the initial position of the present TF path and the aircraft position may differ. To deal with this problem, a circular path method to generate a constrained TF trajectory is proposed.

2. Generation of TF trajectory

TF trajectory is generated assuming that the terrain profile is given. The terrain profile represents 2D terrain information in front of the aircraft. It consists of the terrain's altitude which exists within certain intervals along the flightpath as shown in Fig. 1. There are basic concepts of manoeuvring during TF flight. Aircraft do pull-up, push-

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over, and fly maintaining the climb/dive limit.[9, 10, 11] Pull-up is to raise the flight path angle to pass the high peak terrain safely. Push-over is to control the flight path angle to level flight when the terrain profile is not generated due to the high peak terrain.

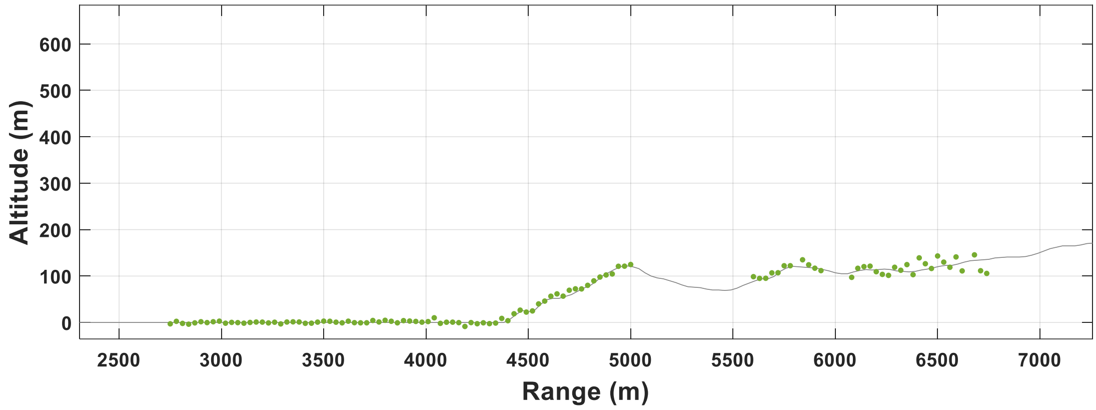

Figure 1: Terrain profile

TF trajectory is generated according to the TF path. The concept of path and trajectory is shown in Fig. 2. The path is a path without time concepts while moving from one point to another, and the trajectory is a path with the concept of time while moving from one point to another. The 3-mask morphology method and the circular path method are used to generate TF path.[12] After the generation of TF path, it is converted into TF trajectory. When generating TF path and trajectory, there are some considerations, such as the aircraft speed, limitation of normal acceleration, limitation of climb/dive angle, and clearance height.[2,3,7,10,12]

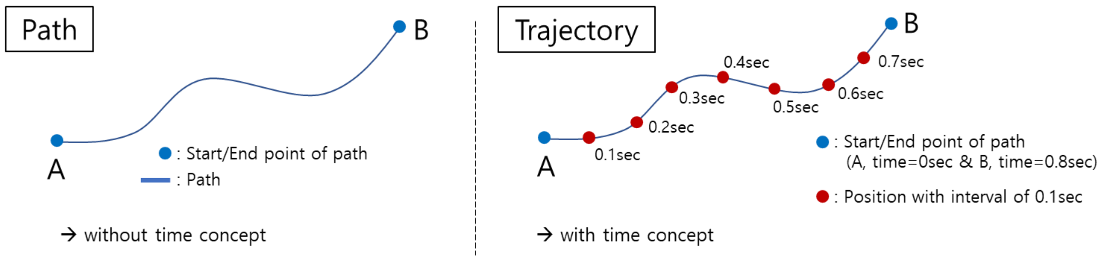

Figure 2: Path vs Trajectory

2.1 Generation of TF path

TF path is generated by using 3-mask morphology method and circular path method. The method to generate TF path using 3-mask morphology consists of four steps. First, the grid size should be determined. Next, according to the grid size, the terrain grid points are determined. The morphology dilation method using 3-mask is conducted. Finally, the waypoints are defined and the result of connecting these points becomes TF path. Figure 3 is the result of conducting 3-mask morphology method.[8]

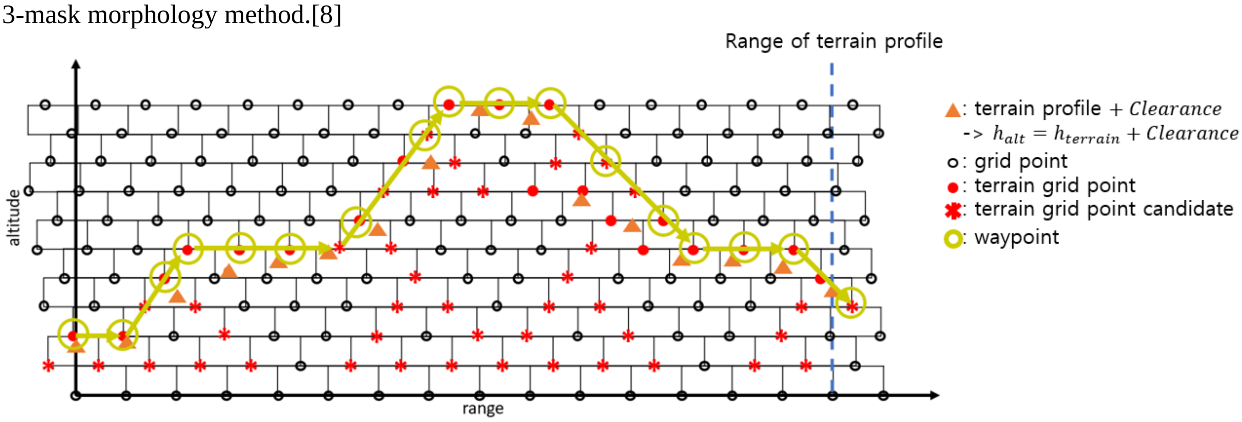

Figure 3: Result of 3-mask morphology

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TF path using 3-mask morphology satisfies the clearance height and the climb/dive angle limits, however, this TF path is still angulated as shown in Fig. 3. Also, TF path using 3-mask morphology only considers the terrain profile, while the position of the aircraft is not considered. To implement TF path, the circular path method is used. The initial position of TF path is constrained by the aircraft position, therefore, while conducting the circular path method, the aircraft position should be considered. Assuming that the aircraft speed is constant, TF path generated by 3-mask morphology is used to create TF path that satisfies the normal acceleration limit of the aircraft and the climb/dive angle limit. As shown in Fig. 4, four types of circular paths are used in circular path method.

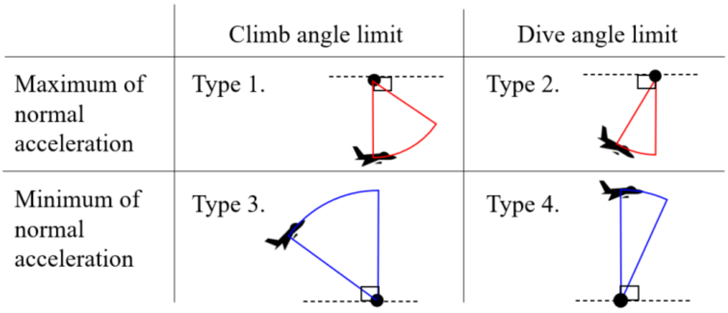

Figure 4: Four types of circular path

The circular path method consists of four steps. Figure 5 represents the process of applying the circular path method. The initial position of TF path is constrained by the aircraft position; thus, the aircraft position is considered in Step 1. If the initial position of TF path and the aircraft position do not match, Step 4 will be conducted.

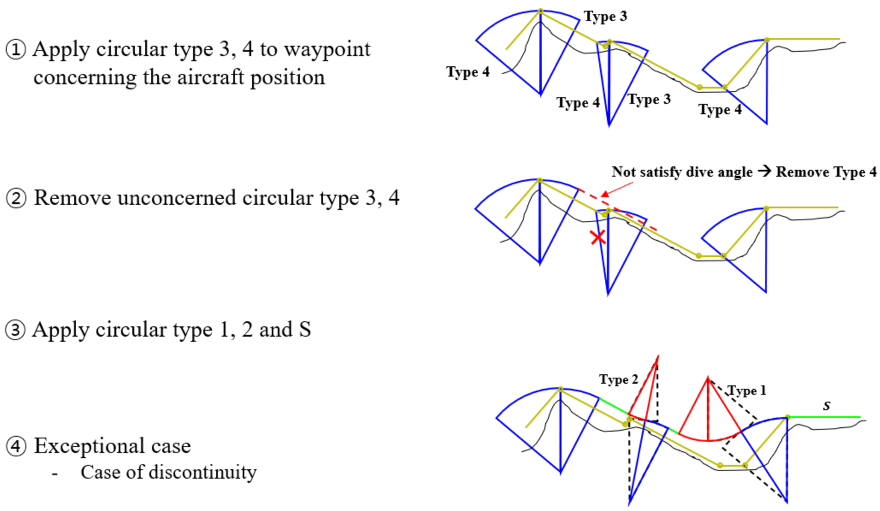

Figure 5: Process of applying the circular path method

First, the circular type 3 and type 4 are applied to the waypoint. TF flight should maintain a certain clearance height and level flight at the peak point. Due to these performance criteria, only the waypoints on the ridge and shoulder are considered. In Step 1, the circular path that the aircraft is flying along should be considered. When the aircraft is flying circular type 3 and type 4, the same circular path would be applied. As shown in Fig. 6, when the aircraft is flying along the circular type 1, the circular type 3 is applied, on the other hand, when the aircraft is flying along the circular type 2, the circular type 4 will be applied. For every generation frequency, the new TF path which is defined as the present TF path would be generated. The first circular path of the present TF path considers the aircraft position. The other circular paths would be applied according to the waypoints of the ridge and shoulder.

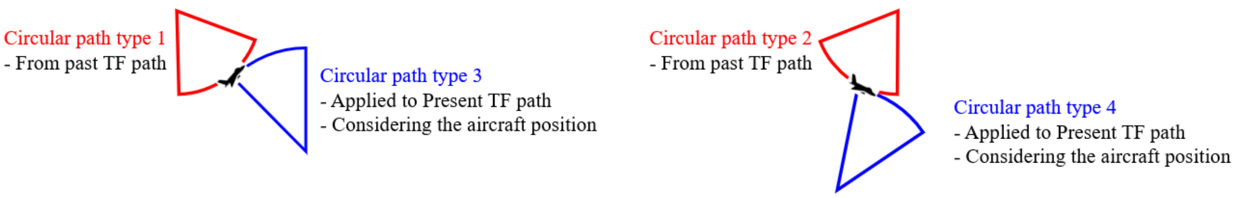

Figure 6: Considering the aircraft position

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Next, the circular type 3 and type 4 which cannot satisfy the climb/dive angle would be removed. Only the circular type 3 and type 4 which satisfy the climb/dive angle, and which can be connected with each other would remain. The circular type 1, type 2 and S are applied to circular type 3 and 4 to connect, while type S means the straight line. As a result, TF path is generated, however, this process sometimes could not generate the flightworthy path as shown in Fig. 7.

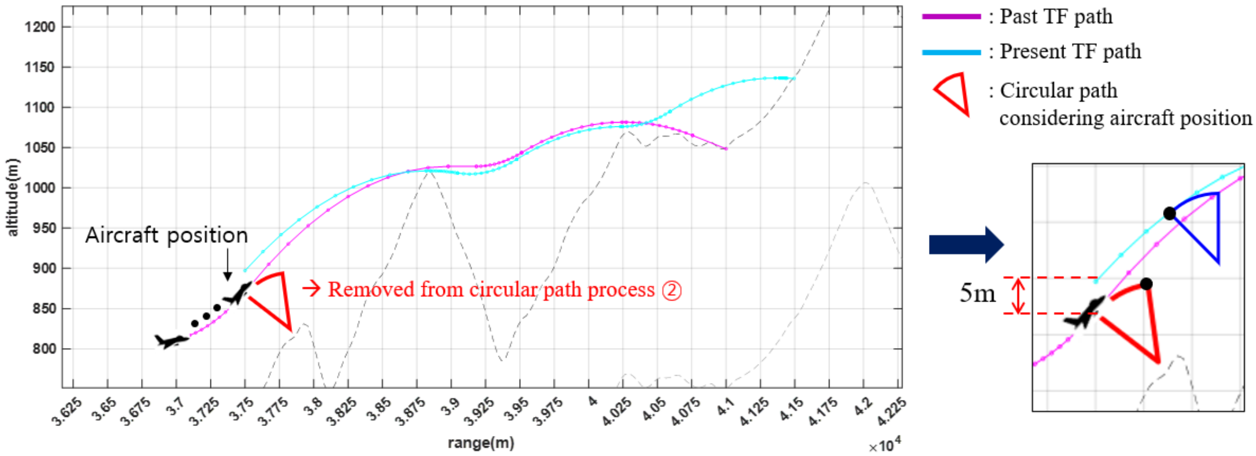

Figure 7: Example of discontinuity

Figure 7 shows the non-flightworthy path which means that the aircraft position and the present TF path are not matched. The criterion of discontinuity is 5m of altitude difference. The discontinuity could have occurred due to the removal of the first circular path in Step 2. The utilized circular path is constrained to satisfy the climb/dive angle limit and normal acceleration limit. However, in the discontinued case, the initial circular path which contains the information of the aircraft position does not satisfy the dive/climb angle within the normal acceleration limit. Therefore, in Step 4, the removed circular path that considering the aircraft position is regenerated and connected with the circular path of the present TF path with an unconstrained circular path. As shown in Fig. 7, the red circular path and the blue circular paths would be connected. As shown in Fig. 8, case ⓐ ~ ⓕ would be considered. Both red and blue circular path could be only circular type 3 and 4. The black boxes on Fig. 8 are same with case ⓔ and ⓕ. To connect the red circular type 3 and blue circular path, the circular type 4 is necessary because the aircraft is diving. Therefore, only the case ⓐ ~ ⓕ needs to be considered by using unconstrained circular path.

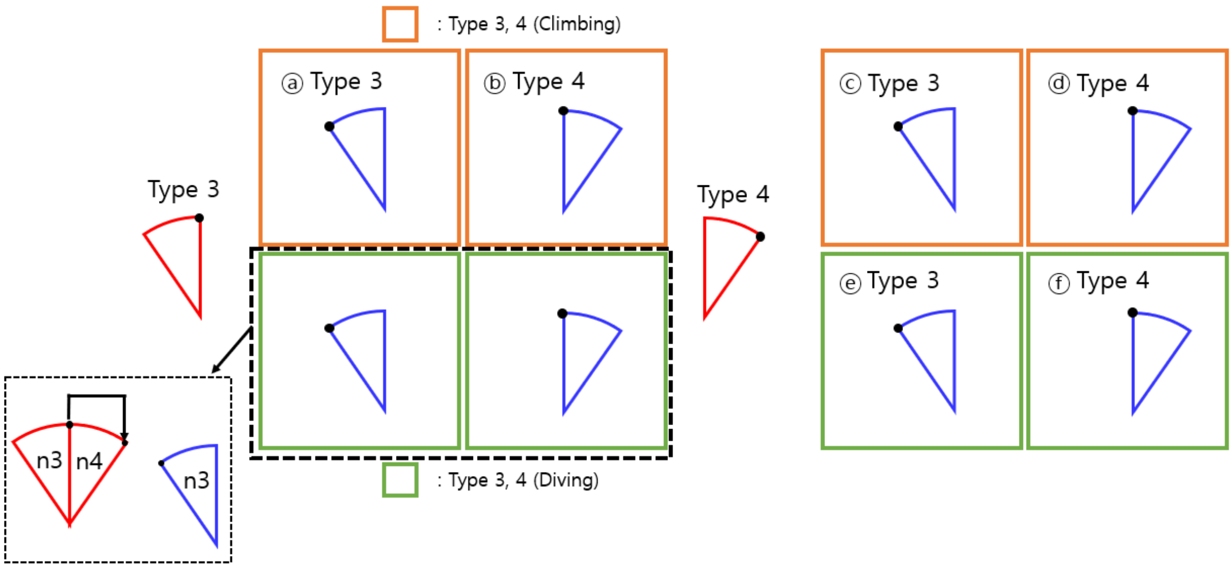

Figure 8: Cases of connection

To determine the way to connect the red and blue circular paths, the intersection of the tangential line is considered. As shown in Fig. 9, the intersection is called as p3, and position of p3 could be classified into two cases. Depending

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on the case, the connecting method of red and blue circular path is different. Figure 10 represents the method used to connect the red and blue circular paths. Case ⓐ ~ ⓕ would be able to connect the red and blue circular paths according to the position of p3.

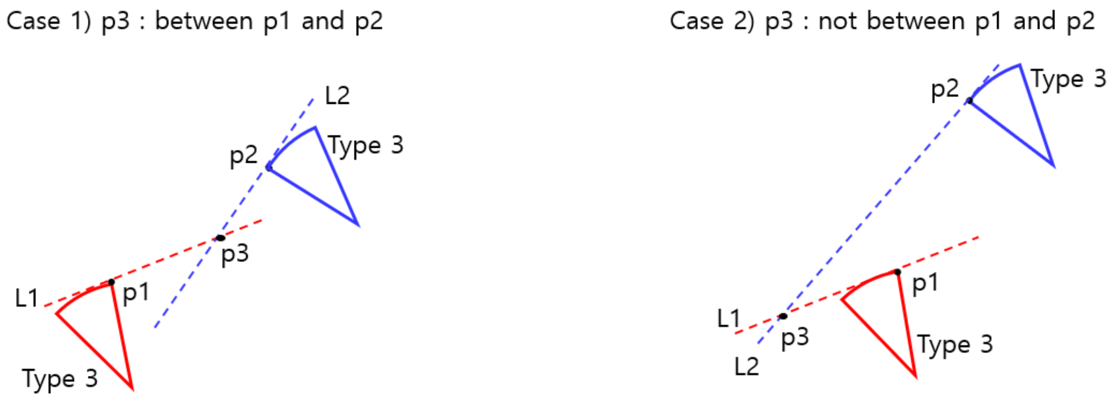

Figure 9: Intersection (p3) of tangential line

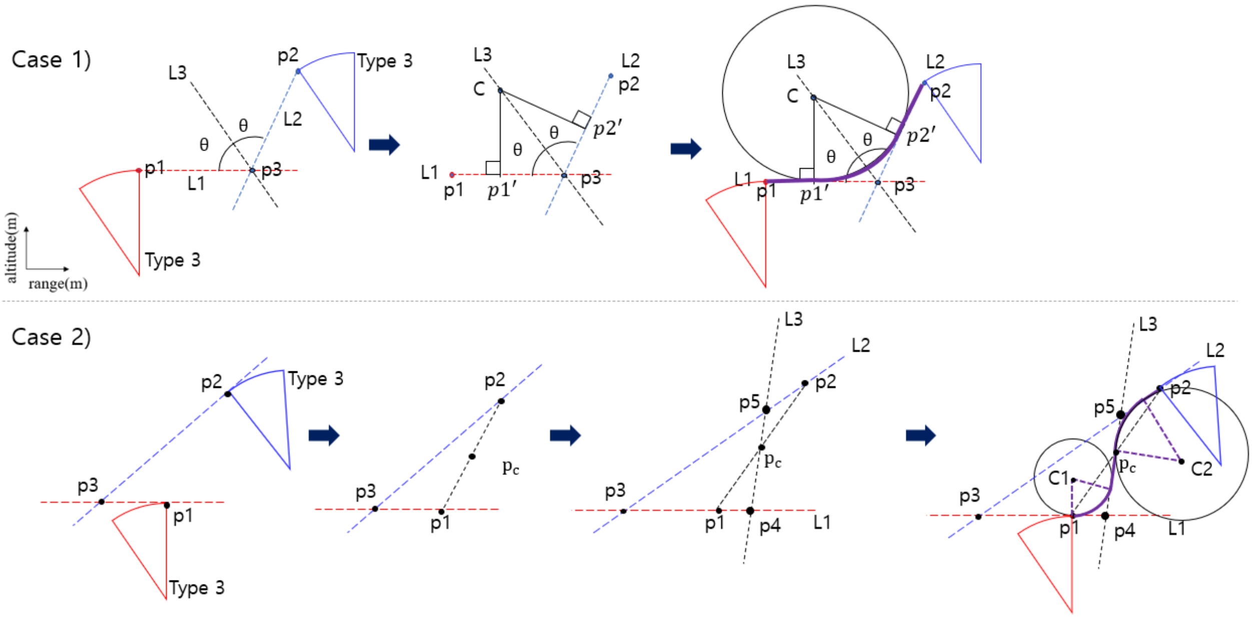

Figure 10: Method to connect the red and blue circular path((a) Up, (b) Down)

2.2 Conversion to TF trajectory

TF path consists of circular path and straight path. The circular path contains the information about the start point and end point, the circular type, and the center of the circle. The straight path contains the information about the start point and end point. By assuming a constant aircraft speed while generating TF path, the radius of the circle is determined. Assuming that TF path is followed at a constant aircraft speed, the time for each circular path can be obtained using Eq. 1. In the case of a straight path, the length between the start point and end point is known, therefore, ΔT can be calculated by dividing by aircraft speed. After ΔT for each path is calculated, TF path is converted into TF trajectory that shows the position, speed, and flight path angle.

$$\dot{\theta} = \frac{aircraft\ speed}{Radius\ of\ circular\ path} \rightarrow \Delta T = \frac{\theta}{\dot{\theta}} \quad \textbf{(1)}$$

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3. Simulation

The simulation of generating TF trajectory is conducted in Jeju Island. Table 1 shows the considerations of TF trajectory. The terrain profile is provided in every second with a length of 4km.

Table 1: Consideration

Consideration	Value
Aircraft speed	250m/s
Normal acceleration limit	-0.9g ~ 2g
Climb/dive angle limit	-15° ~ 30°
Clearance height	1000ft

According to the generation frequency, TF trajectories are generated as shown in Fig. 11. The length of the generated TF trajectory is 4km due to the length of the terrain profile.

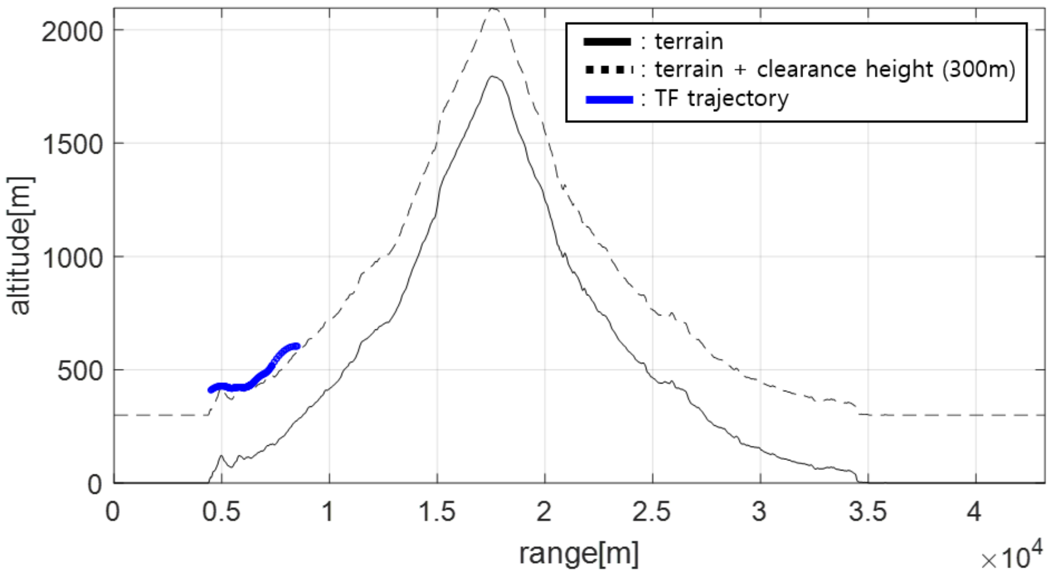

Figure 11: TF trajectory

The tracking simulation uses an aircraft mass kinematics model with 3 degrees of freedom in a two-dimensional plane using Eq. (2) ~ (5). The normal acceleration limit is generally an acceleration in the normal direction, including gravitational acceleration. It is assumed that the acceleration includes gravitational acceleration. The effects of the wind are not considered.

$$\dot{x} = V cos\gamma \quad \textbf{(2)}$$

$$\dot{h} = V sin\gamma \quad \textbf{(3)}$$

$$\dot{V} = a_{t,rot} \quad \textbf{(4)}$$

$$\dot{\gamma} = a_{n,rot}/V \quad \textbf{(5)}$$

However, there are unconstrained circular paths that are not able to satisfy the climb/dive angle limit or normal acceleration limit. To make aircraft fly along the unconstrained circular path, the tracking simulation was conducted with compensation as shown in Fig. 12.

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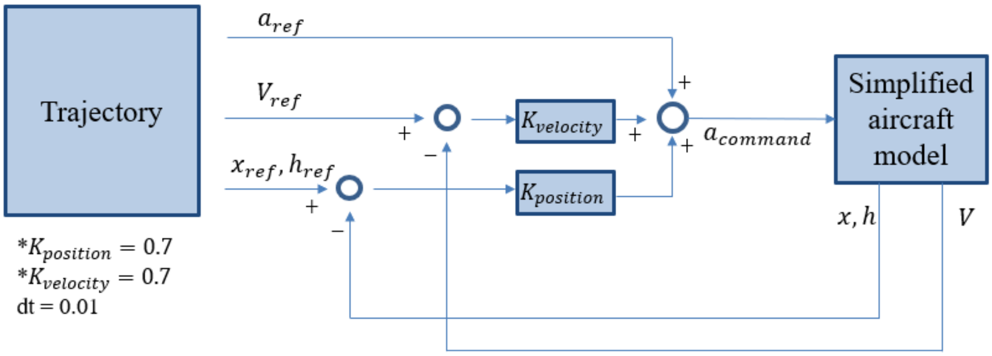

Figure 12: Tracking simulation

The results of tracking simulation refer that the aircraft kinematic model performs TF flight along the trajectory with the aircraft normal acceleration command which is generated from the trajectory. Figure 13 shows the result of TF trajectory and the tracking simulation in Jeju. The considerations, such as constant speed, climb/dive angle and normal acceleration were calculated. The left figure of Fig. 13 represents TF trajectory and the result of tracking simulation. The right upper figure of Fig. 13 represents aircraft speed while the lower figure shows the climb/dive angle.

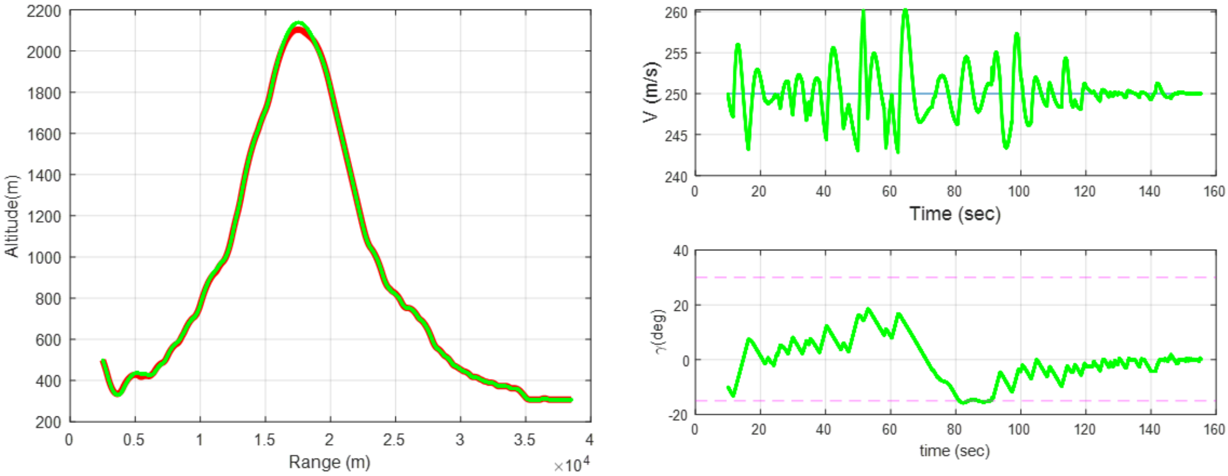

Figure 13: Result of tracking simulation

4. Conclusion

TF flight could minimize the risks of being revealed to the enemy while maintaining the clearance height. The proper TF trajectory is necessary for minimizing the risks. TF trajectory is generated according to the terrain profile which is generated at a certain frequency. Therefore, there are some constraints on the initial and terminal positions while generating TF trajectory. In this paper, the constrained TF trajectory generation algorithm is proposed. There are several considerations such as the normal acceleration limits, climb/dive angle limits, and aircraft speed while generating the TF trajectory. TF path is generated by using 3-mask morphology method and circular path method. 3-mask morphology method is utilized to generate TF path that satisfies the clearance height and clime/dive angle limits. The circular path method is utilized to make TF path smooth, and it satisfies the normal acceleration limits, climb/dive angle limits, and the constraint of aircraft position. Finally, TF path is converted into TF trajectory. Through the simulation, the generated TF trajectory is represented. By tracking simulation, it represented that the aircraft model could follow the generated TF trajectory. The aircraft speed is assumed as constant 250m/s, however, through the tracking simulation, the aircraft speed shows 240 ~ 260m/s. The limitation of climb and dive angle is satisfied. It takes 0.02 seconds for generating TF trajectory in Inter i7-11700@2.5GHz CPU environment. The proposed method could be applied in real time due to the less computation time.

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